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**TERFENOL-D Lamination Process Cost Reduction
Final Technical Report**

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Abstract

The process of manufacturing laminated TERFENOL-D is costly and time consuming. This Phase I study was aimed at reducing the reject rate of the current lamination process and thus reducing the cost of laminated TERFENOL-D. Current stringent requirements call for infinite resistance between lamina. These requirements can lead to reject rates as high as 50%. Analytical calculations indicate that somewhat less than infinite interlaminar resistance is needed for eddy current reduction.

This experimental study investigated the effects of less-than-infinite glue joints on eddy current losses. Test fixtures and methods were designed to compare solid rods and laminated rods with various interlaminar resistances. Initial results show a significant difference between solid rods and rods with less-than-infinite resistance. While there was some indication of a difference, the difference between infinite and less-than-infinite interlaminar resistance was within variance of the test procedure.

I. Introduction

TERFENOL-D was invented by the U.S. Navy to increase its capability in sonar power and range. Because TERFENOL-D has a higher energy density than current technologies, it can be used to produce more powerful and smaller sonar devices. However, the cost of TERFENOL-D is higher than competing technologies. One factor contributing to the cost is lamination of the material. Typically, TERFENOL-D must be laminated if it is operating above 500 Hz. If the TERFENOL-D is not laminated, large losses are incurred due to eddy currents in the material. As other TERFENOL-D manufacturing costs are reduced, the relative cost of laminating will continue to increase.

There are two approaches that can be taken to reduce the cost of laminated TERFENOL-D. The first is to improve the overall lamination process and the second is to increase the yield of the current lamination process. Improving the overall lamination process may be addressed in a Phase II effort. Therefore, this work addressed increasing the yield of the current lamination process.

Current thinking is that adjacent laminae must be totally electrically isolated from one another, thus producing infinite measured resistance between the laminae. It is thought that if the measured resistance is less than infinite, the eddy current reduction of the glue joint has been reduced or nullified. Lamination is a lengthy and costly process. If a TERFENOL-D specimen is rejected at the test phase due to less than infinite measured resistance, the entire specimen must be scrapped and the process started over. Reject rates can be as high as 50% using an infinite resistance specification.

Some preliminary theory shows that interlaminar resistance need only be in the milliohm range to create an effective eddy current barrier. The purpose of this Phase I study was to experimentally verify that interlaminar resistance can be significantly lower than infinity to create an effective eddy current barrier.

The study was completed by producing sample TERFENOL-D rods of a pre-determined number of laminae with varying levels of interlaminar resistance. A test actuator was built and qualified for the purpose of performing tests on the specified samples of TERFENOL-D. Upon completion of the necessary tests, statistical analyses were performed on the data and recommendations made. The final product of the Phase I Option is intended to be a specification for interlaminar resistance that will be accepted as the industry standard.

II. Test Equipment and Methods

This section describes in detail the test samples, apparatus, conditions, and methods used. The purpose of this experimental study was to investigate the effect of less-than-infinite interlaminar resistance on TERFENOL-D performance.

A. Test Samples

This section describes the samples used in the tests.

1. Sample Size

The sample size was 10 mm diameter by 35 mm length. The samples had 3 laminae (2 glue joints). The critical frequency for eddy current generation with a skin depth of δ is given by the equation [1]

$$f_c = \frac{\rho}{\pi \delta^2 \mu_0 \mu_r}$$

where f_c is the critical frequency in Hz, μ_0 is the permeability of free space, μ_r is the relative permeability of TERFENOL-D, ρ is the resistivity of TERFENOL-D, and δ is the eddy current skin depth. With $\mu_r = 5.0$, $\rho = 58 \times 10^{-8}$ ohm-m, and $\delta = 3.33$ mm the critical frequency is 2700 Hz. If the laminations are designed to be two eddy current skin depths thick, $2\delta = 3.33$ mm, the critical frequency is 10800 Hz. The laminae thickness of two eddy current skin depths was chosen because that is the standard generally used for eddy current reduction. However, in designs where eddy current generation is critical, an optimum thickness less than one eddy current skin depth is chosen. The resonance of the actuator was designed to fall between these two frequencies. This choice ensures that while there will be some eddy current generation in an infinite resistance laminated rod, the eddy currents will not be overwhelming in the actuator response.

2. Epoxy and Interlaminar Resistance

Upon investigation of available epoxies, it was found that commercially available epoxies are generally either electrically conductive ($\rho < 10^{-3}$ ohm-cm) or electrically insulative ($\rho > 10^{13}$ ohm-cm). There are very few epoxies that fall between these levels. Interlaminar resistances in the range from 10 milliohms to 10,000 ohms were to be studied. These resistances correspond to resistivities in the range of 3.5 ohm-cm to 3.5×10^6 ohm-cm.

To produce the desired interlaminar resistances a two part epoxy with no fillers was filled with varying amounts of silver powder to change the resistivity of the epoxy. The resin used was EPON™ 828 from Shell Chemicals and the hardener used was EPICURE™ 3234 also from Shell Chemicals. Epoxy samples were prepared for testing by an outside laboratory. Testing, using ASTM D-4496 as a reference, indicated that the samples were in the desired ranges of resistivities, 20% silver powder (4 ohm-cm), 10% silver powder (200 ohm-cm), and 5% silver powder (4×10^{15} ohm-cm). The samples with 10% and 5% silver powder had more variability in the results than the 20% sample. These test results can be found in Appendix C.

3. Laminated Samples

Four different levels of resistance were desired with five samples of each resistance including infinite resistance. However, when the samples were produced, it was found that only the epoxy with the maximum amount of silver powder and the epoxy with no silver powder produced consistent samples. Five laminated rods with interlaminar resistances between 0.5 and 5 ohms were produced. Five laminated rods with infinite (> 1 megaohm) interlaminar resistances were produced. Seven samples with interlaminar resistances between 10 ohms and 500 ohms were produced. The produced samples are listed in Table 1.

	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6	Rod 7
No resistance (solid)	X	X	X	X	X		
Level 1 resistance (0.5-5 ohms)	X	X	X	X	X		
Level 2 resistance (10-500 ohms)	X	X	X	X	X	X	X
Infinite resistance	X	X	X	X	X		

Table 1. Samples produced for testing.

B. Test Apparatus and Test Methods

This section describes the test apparatus and the methods of operation for the test apparatus.

1. Test Apparatus

A schematic of the test fixture is shown in Figure 1. The test fixture consists of a DC bias coil, an AC cell consisting of the drive coil, flux return materials, Belleville springs to preload the TERFENOL-D rod, test probe holders, a preload cap, an output push rod, and a base to hold all components in place. An accelerometer was placed on the top of the output rod to measure the output acceleration.

The drive coil was made with Litz stranded coil wire to reduce the heating of the coil due to eddy currents. Permanent magnets are not conducive to easy assembly and disassembly of the transducer because many times they must be demagnetized and remagnetized with each assembly. Therefore, the magnetic biasing of the TERFENOL-D sample was accomplished using a DC bias coil. The DC bias coil allows the biasing field to be easily turned off and makes the biasing very repeatable by controlling the current into the coil. An air gap existed between the DC coil and the AC cell so as not to heat the AC cell due to the current in the DC coil. Advanced magnetic flux materials were used in the magnetic circuit to give a fairly uniform field ($\pm 10\%$) over the TERFENOL-D sample. The preload cap compresses Belleville springs and causes preloading of the rod. The preload was controlled by measuring the distance between the top of the accelerometer and the top of the preload cap.

The test fixture was designed for very specific performance. The first resonance of the actuator was designed to be approximately 6 kHz. A prestress of 13.8 MPa \pm 1.5 MPa was applied to the TERFENOL-D samples in the fixture. The DC magnetic bias field was 40,000 A/m (500 Oe) and the AC magnetic field was sinusoidal with a magnitude of \pm 16,000 A/m (200 Oe). These magnetic conditions operate the TERFENOL-D in the most "linear" region of the strain curve. The test actuator was designed to be rigid in the frequency range of interest, thus eliminating any unwanted vibrations.

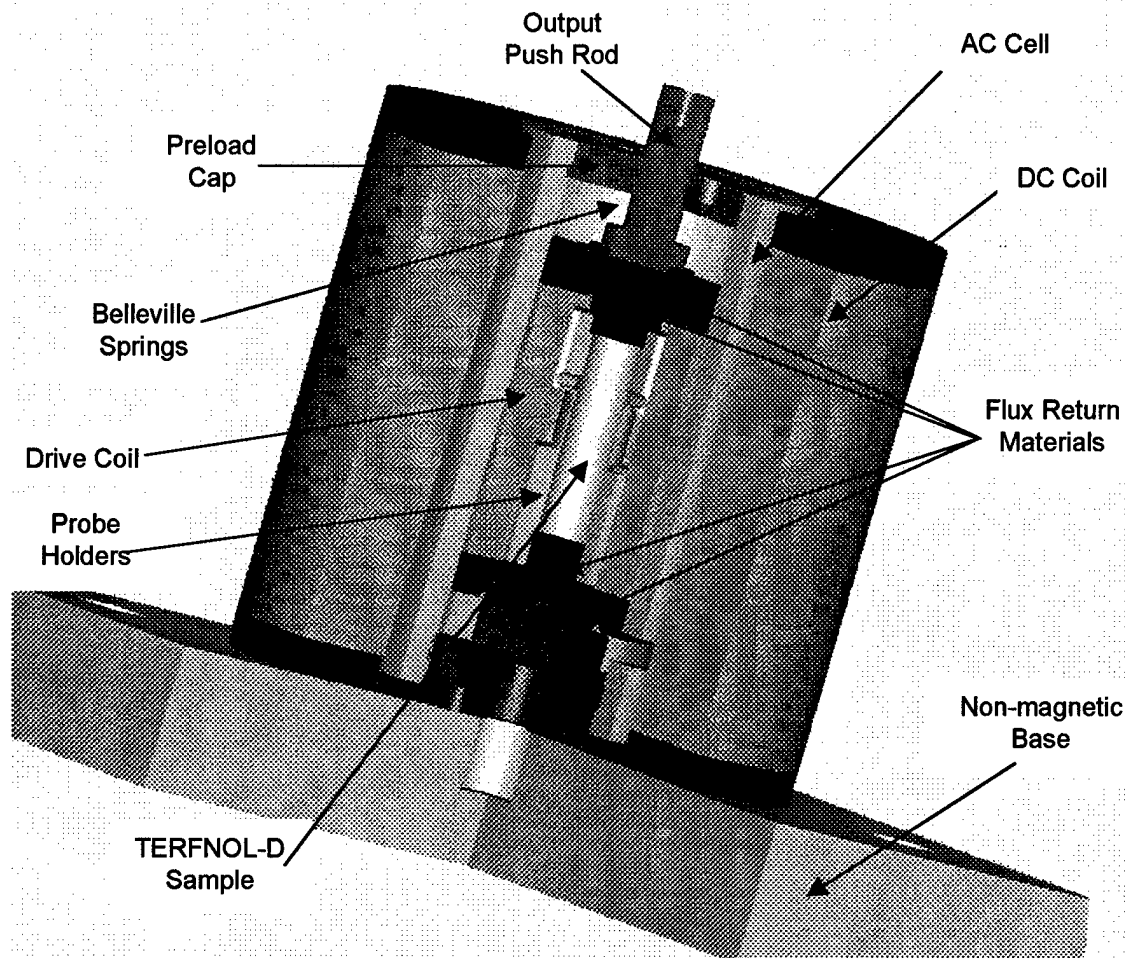


Figure 1. Schematic of the Test System

2. Test Methods

The tests were performed under specific conditions determined during the validation and check of the test system. A swept sine using a constant voltage input from 4000 to 7500 Hz by increments of 11.7 Hz was used to excite the TERFENOL-D sample. The center of the frequency range was near the fundamental resonance of the TERFENOL-D sample.

Parameters monitored included input current, voltage across the transducer leads, output acceleration, and temperature of the TERFENOL-D sample. These parameters provided enough flexibility to determine the effects of interlaminar resistance. Figure 2 is a wiring diagram indicating how the monitoring equipment was connected to the system. The temperature of the test sample was measured prior to testing and immediately after testing to determine the temperature rise. A detailed test procedure for operating the fixture is presented in Appendix A.

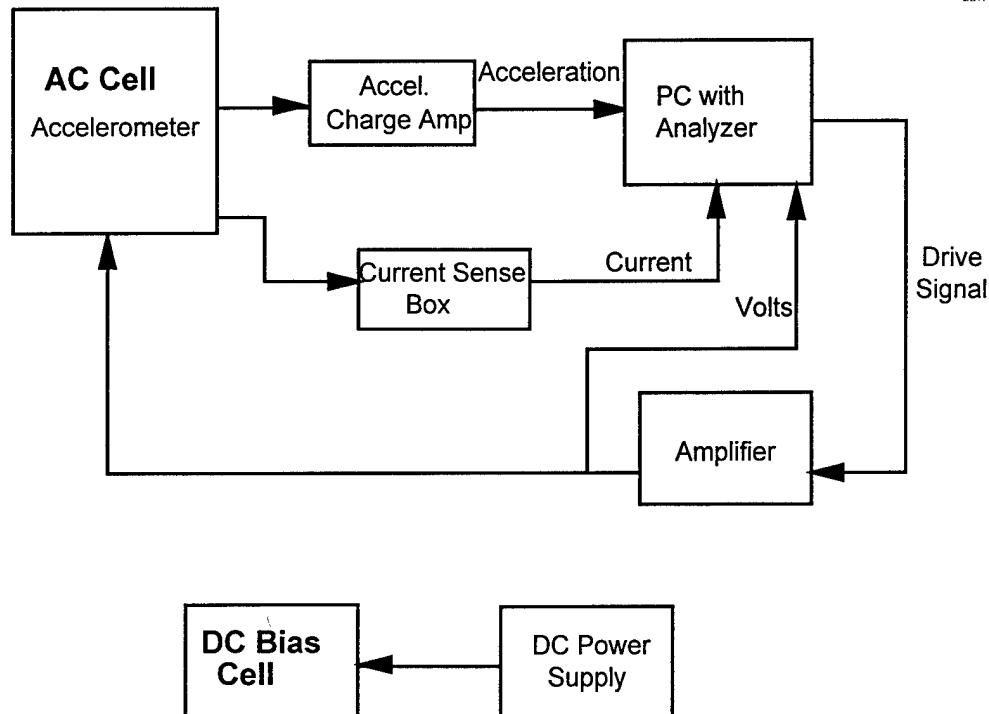


Figure 2. Wiring Diagram of the Test System

III. Validation Tests

A. Test Plan

Before the full series of tests were performed, the test procedure and apparatus were put through a battery of tests to validate the methods used. From these initial tests, the test procedure was modified and refined to get the best possible results.

1. Scope of Validation Tests

The first battery of tests was multipurpose. The first purpose of the validation tests was to refine the test methodology and test procedures. The second purpose was to determine the variability of the test actuator and procedures. The third purpose of these tests was to determine the variability between TERFENOL-D samples. The final purpose of the validation tests was to determine whether the system had the resolution to distinguish between laminated and solid TERFENOL-D samples.

2. Variable Identification

Table 2 lists the variables (as well as whether they are controllable or not) involved with the tests performed.

<i>Variable name</i>	<i>Control Level</i>	<i>Fixed or Varied</i>
Prestress	Controlled	Fixed
Drive levels	Controlled	Fixed
Epoxy – material properties	Controlled	Varied
Epoxy – thickness	Controlled	Fixed
Number of laminae	Controlled	Fixed
TERFENOL-D stoichiometry	Controlled	Fixed
Machining tolerances of samples	Controlled	Fixed
Frequency	Controlled	Varied
Loading	Controlled	Fixed
Sample temperature	Uncontrolled	Fixed
Coil temperature	Uncontrolled	Fixed

Table 2. Variables and control level.

3. Test Samples

For the initial validation tests, there were 10 test specimens. Five of the pieces were solid TERFENOL-D rods, and five were identically laminated with infinite resistance between laminae. An infinite resistance glue joint was defined as one with a resistance greater than 1 megaohm. All ten samples had the same dimensions. A more complete sample description including dimensions can be found in Section II. A.

4. Experimental Matrix

The test procedure was refined and revised during some initial tests. The data from these tests were not saved. After the test procedure was defined, five tests were run on each of the 10 samples to characterize the test system.

B. Results and Analysis

Data collected were current, voltage, and acceleration. Several types of analyses were performed on the data. The current and voltage were used to calculate complex impedance and also input power. Using acceleration and mass information, output mechanical power was calculated.

1. Analysis Methods

The real and imaginary parts of the electrical impedance can be used to produce a Nyquist plot. A typical Nyquist plot is shown in Figure 3. From the Nyquist plot, insight into the transducer performance and losses can be gained. The potential

efficiency of a transducer can be calculated by [2]

$$\eta_{potential} = \frac{\sqrt{R_{max}} - \sqrt{R_{min}}}{\sqrt{R_{max}} + \sqrt{R_{min}}} * 100\%$$

where R_{max} and R_{min} are the maximum and minimum real parts of the complex impedance. The loss tangent can also be calculated from the Nyquist plot as the angle from the crossover point of the Nyquist plot to the center of the circle as indicated in Figure 3.

The Nyquist plot should approximate a circle. Therefore, in order to obtain the most reliable results, a computer program was written to process the data. First the crossover point was found, then the data was divided at the crossover point, next a circle was fit in the least squares sense to the data using the center point location and the radius as variables. Potential efficiency and loss tangent calculations were made on the fitted data in order to eliminate noise effects. The computer code used in this processing is listed in Appendix B.

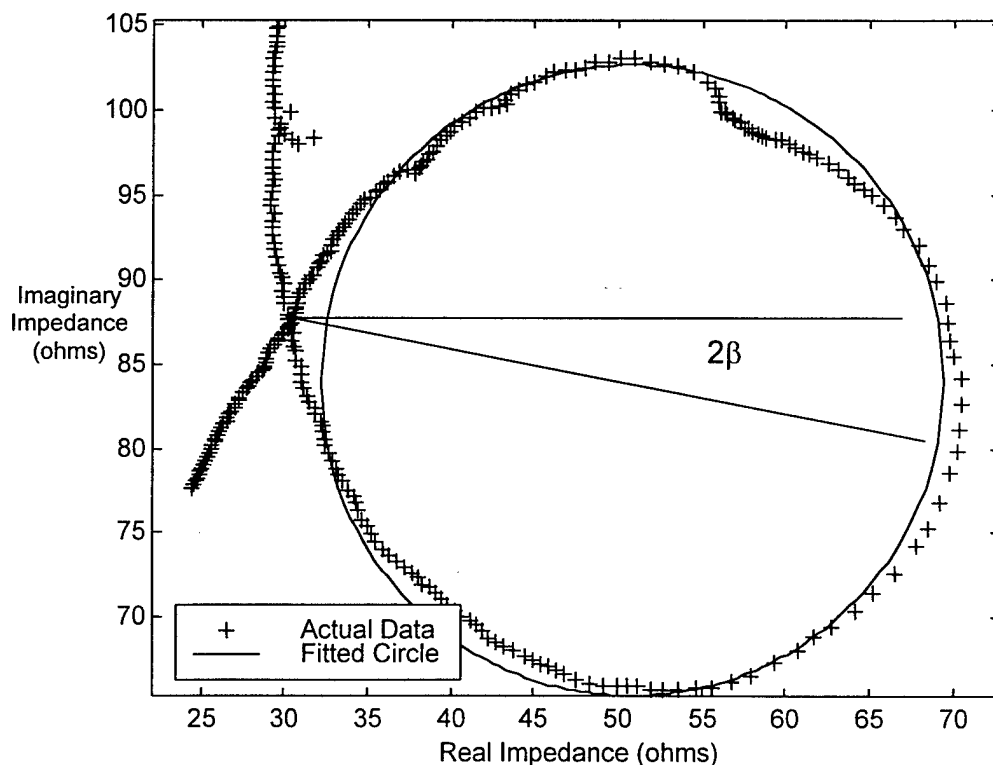


Figure 3. Typical Nyquist plot and a circle fitted to the data

The input electrical power and the output mechanical power can be used to calculate the electromechanical efficiency of the transducer.

$$\eta_{em} = \frac{P_{out}}{P_{in}} * 100\%$$

These three parameters, potential efficiency, loss tangent, and electromechanical efficiency, were calculated for all the validation tests.

2. Summary of Results

This battery of tests was multipurpose. The first purpose of the validation tests was to refine the test methodology and test procedures. The second purpose was to determine the variability of the test actuator and procedures. The third purpose of these tests was to determine the variability between TERFENOL-D samples. The final purpose of the validation tests was to determine whether the system had the resolution to distinguish between laminated and solid TERFENOL-D samples. The data presented in this section were taken with the final test procedure in place. Table 3 presents potential efficiency calculated as described above for each of the validation tests. Because the Nyquist plots for the solid rods were not very circular, the loss tangent calculated from the fitted circle was not very repeatable. Therefore, only the potential efficiency and electromechanical efficiency data were used in calculations.

Figure 4 is a notched box plot of the solid and laminated potential efficiency validation data. Each number along the x direction represents a set of five tests on a single test sample. The upper and lower lines of the "box" are the 25th and 75th percentiles of the sample. The line in the middle of the box is the sample median. When the median is not in the center of the box, it indicates that the data is skewed. The lines extending from the top and bottom of the box indicate the range of the data. In spite of the large variance calculated for the data, Figure 4 shows a distinct difference between the potential efficiency of the solid samples and the laminated samples. The test system has the required sensitivity to distinguish between solid and laminated samples.

Figure 5 is a notched box plot of electromechanical efficiency. The electromechanical efficiency also shows a large difference between the solid and laminated samples. However, the values of these data do not cover as large a range as the potential efficiency data. Therefore, the potential efficiency data were used to calculate the variances of the system.

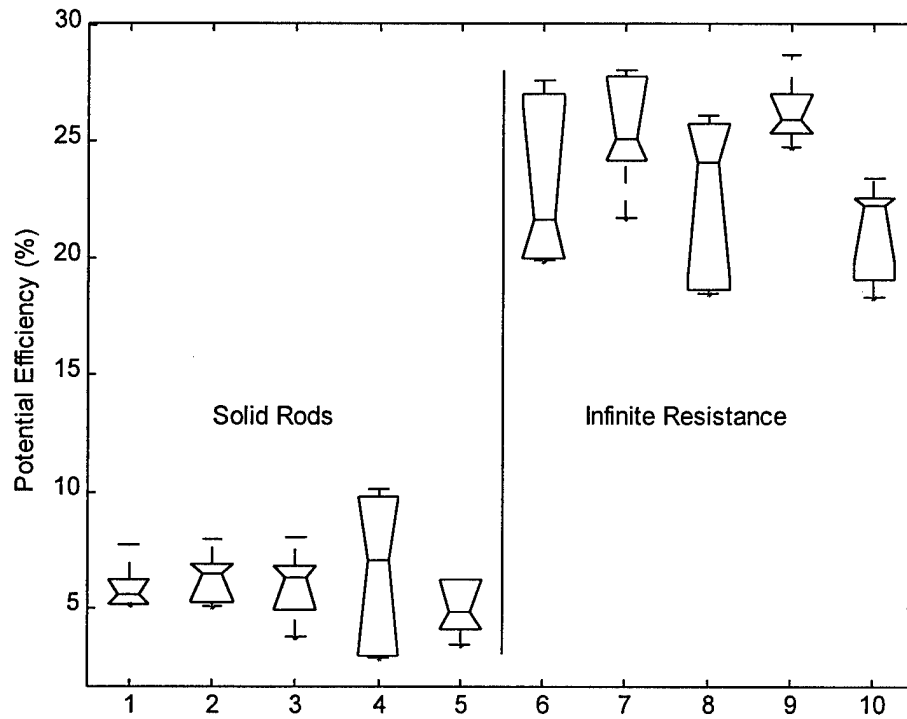


Figure 4. Box plot of Potential Efficiency Validation Test Data

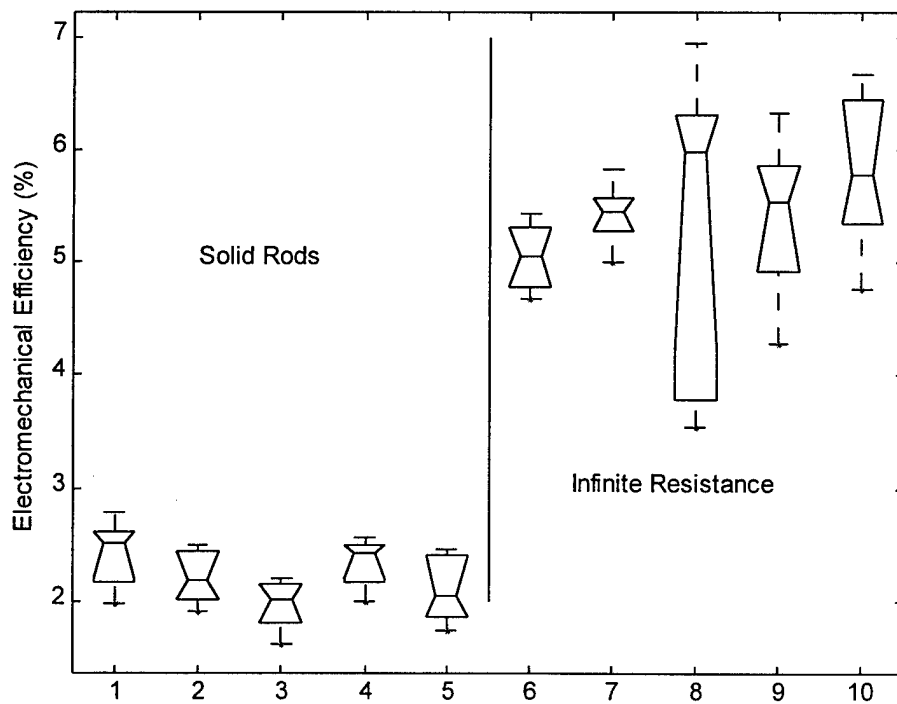


Figure 5. Box plot of Electromechanical Efficiency Validation Test Data

	Solid					Laminated				
	<i>Rod 1</i>	<i>Rod 2</i>	<i>Rod 3</i>	<i>Rod 4</i>	<i>Rod 5</i>	<i>Rod 1</i>	<i>Rod 2</i>	<i>Rod 3</i>	<i>Rod 4</i>	<i>Rod 5</i>
Test 1	5.2	5.1	8.1	9.7	4.4	27.7	28.0	18.8	26.4	19.3
Test 2	5.6	6.5	6.3	2.9	4.9	26.9	27.8	26.1	25.6	22.3
Test 3	5.8	5.3	6.5	7.1	6.3	20.1	21.8	25.7	24.8	23.4
Test 4	7.8	8.0	3.8	3.0	3.4	21.7	25.2	18.5	28.8	18.4
Test 5	5.2	6.6	5.3	10.2	6.3	20.0	25.1	24.1	26.0	22.3

Table 3. Potential efficiency results for validation tests

In order to find the variance of the test system, the sum of the squares was calculated for the set of 5 tests on each rod [3].

$$SS_0 = \sum X_i^2 - \frac{(\sum X_i)^2}{N}$$

SS_0 is the sum of the squares, X_i is the test result for each test, and N is the number of tests. Next, the testing variance was computed by summing all the sum of squares and dividing by the total number of degrees of freedom [3].

$$\sigma^2 = \frac{\sum SS_0}{df}$$

In this case $df = 40$. The testing variance was calculated to be 6.0. The variance between rods was calculated by using the mean of the five tests for each rod and then calculating the sum of squares for the means. Finally, using the last equation to calculate the variance. The variance of the TERFENOL-D rods was calculated to be 12.1. There is a large variance in the test system and also between the TERFENOL-D samples. However, the test system still has the sensitivity to distinguish between solid and laminated samples.

IV. Resistance Study Tests

This section describes the test plan and the experimental results for the variable resistance study.

A. Experimental Test Plan

A test plan using the samples as described in Section II.A was developed. This section describes the scope of the tests.

1. Scope of Resistance Study Tests

The purpose of the resistance study tests was to determine the effect of interlaminar resistance on the power loss of the system due to eddy currents. Test results will be compared with theoretical calculations in the Phase I Option.

In the context of this report, comparative measures were used to obtain meaningful results about interlaminar resistance.

2. Variables

Table 4 lists the variables (as well as whether they are controllable or not) involved with the tests performed.

<i>Variable name</i>	<i>Control Level</i>	<i>Fixed or Varied</i>
Prestress	Controlled	Fixed
Drive levels	Controlled	Fixed
Epoxy – material properties	Controlled	Varied
Epoxy – thickness	Controlled	Fixed
Number of laminae	Controlled	Fixed
TERFENOL-D stoichiometry	Controlled	Fixed
Machining tolerances of samples	Controlled	Fixed
Frequency	Controlled	Varied
Loading	Controlled	Fixed
Sample temperature	Uncontrolled	Fixed
Coil temperature	Uncontrolled	Fixed

Table 4. Variables and control level

3. Sample List

For the resistance study tests, there were a total of 22 test pieces. Five of the pieces were solid TERFENOL-D rods. Five were identically laminated with infinite resistance between lamina. Five were laminated with 0.5-5 ohm interlaminar resistance. Seven were laminated with 10-500 ohm interlaminar resistance. A more complete sample description including dimensions can be found in Section II. A.

4. Experimental Matrix

Each of the samples was tested 5 times. The test matrix is shown in Table 5. It is readily apparent that the tests on the solid samples and the infinite resistance samples were completed in the validation tests. As the test procedure did not change from the time the validation tests were completed, these tests were not repeated.

		<i>Rod 1</i>	<i>Rod 2</i>	<i>Rod 3</i>	<i>Rod 4</i>	<i>Rod 5</i>	<i>Rod 6</i>	<i>Rod 7</i>	<i>Rod 8</i>
<i>No resistance (solid)</i>	Test 1	X	X	X	X	X			
	Test 2	X	X	X	X	X			
	Test 3	X	X	X	X	X			
	Test 4	X	X	X	X	X			
	Test 5	X	X	X	X	X			

<i>Level 1 resistance (0.5-5 ohms)</i>	Test 1	X	X	X	X	X			
	Test 2	X	X	X	X	X			
	Test 3	X	X	X	X	X			
	Test 4	X	X	X	X	X			
	Test 5	X	X	X	X	X			
<i>Level 2 resistance (10-500 ohms)</i>	Test 1	X	X	X	X	X	X	X	X
	Test 2	X	X	X	X	X	X	X	X
	Test 3	X	X	X	X	X	X	X	X
	Test 4	X	X	X	X	X	X	X	X
	Test 5	X	X	X	X	X	X	X	X
<i>Infinite resistance</i>	Test 1	X	X	X	X	X			
	Test 2	X	X	X	X	X			
	Test 3	X	X	X	X	X			
	Test 4	X	X	X	X	X			
	Test 5	X	X	X	X	X			

Table 5. Resistance study test matrix

B. Results and Analysis

This section describes the analyses performed on the resistance sample data and the results of these analyses.

1. Analysis Methods

As determined from the validation tests, the potential efficiency, as calculated from methods described in Section III.B.1, gives a comparative measure of TERFENOL-D rod performance. Electromechanical efficiency also gives a measure of TERFENOL-D rod performance. Potential efficiency and electromechanical efficiency were used as metrics for the resistance samples.

There were two questions that needed to be answered by these tests. First, do the efficiencies of the less-than-infinite resistance samples differ from the efficiencies of the solid samples? If so, by how much? Secondly, do the efficiencies of the less-than-infinite resistance samples differ from the efficiencies of the infinite resistance samples? If so, by how much? These questions were answered using two methods. A notched box plot representation gives a visual representation of the data. Hypothesis testing gives a statistical measure of the results.

2. Test Results

Figure 6 is a box plot including potential efficiency data for all the samples. A distinct difference between the solid rods and all the laminated rods is clearly shown. A description of the box plot can be found in section III.B.2.

The medians for all the solid rods fall below 10% while the medians for all the laminated rods fall above 15%. Except for one outlying data point, indicated by a + on the plot, there is no overlap in the data. Therefore, it is reasonable to state that less-than-infinite interlaminar resistance is an improvement over no lamination.

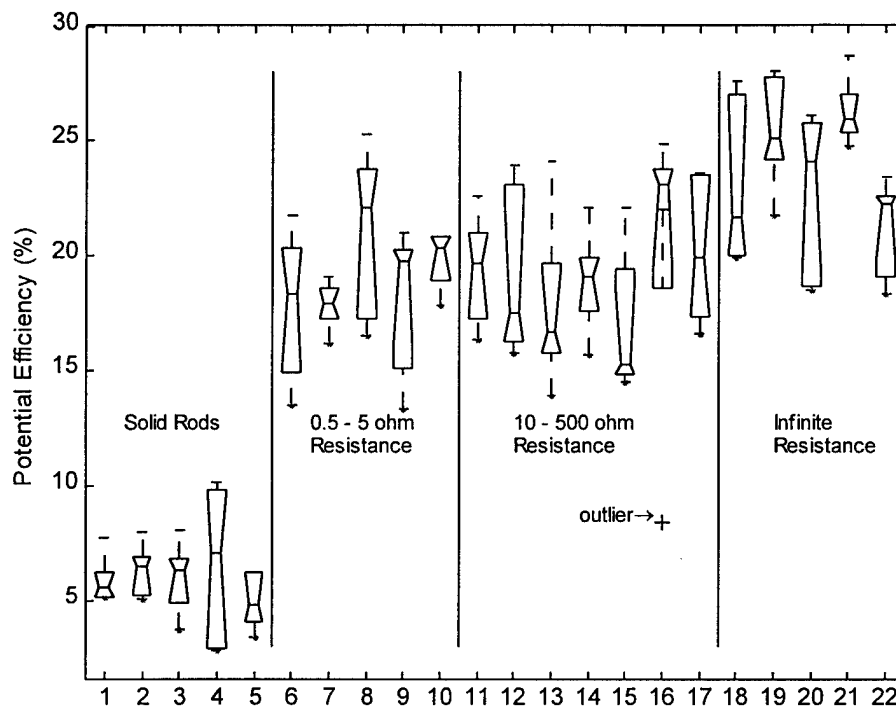


Figure 6. Consolidated potential efficiency data for all samples

Figure 7 shows a consolidated electromechanical efficiency plot for all samples. The data shows a difference between the solid samples and all of the laminated samples. However, because the spread of the data does not cover the same numerical range as the potential efficiency, the electromechanical efficiency data will not be analyzed further in this section.

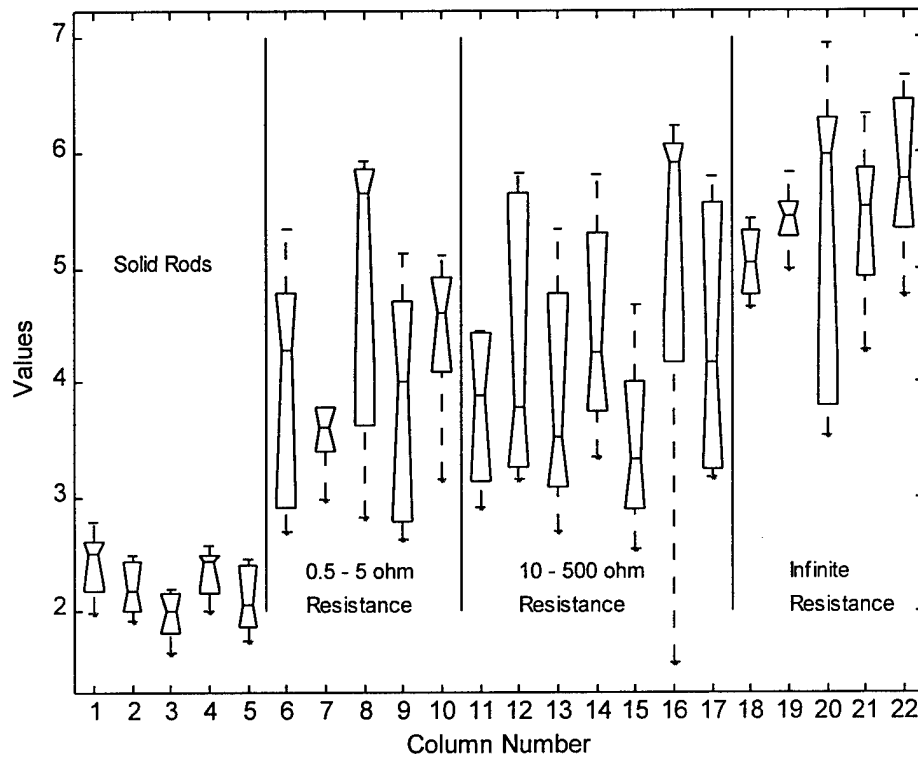


Figure 7. Consolidated electromechanical efficiency data for all samples

Figure 8 shows a notched box plot of the potential efficiency for all the laminated samples. While there appears to be some difference between the less-than-infinite sample data and the infinite sample data, there is significant overlap in the data. The box plot cannot give any more useful information in comparing the laminated samples.

Figure 9 is a box plot of the electromechanical efficiency data for all the laminated samples. The plot shows similar variation and spread of the data as in the potential efficiency. Therefore, hypothesis testing was not completed for these data.

Hypothesis testing was used to further investigate the results. The potential efficiency mean of the infinite laminated samples was calculated to be 23. 8%. The sample data for each rod were hypothesis tested against this mean. The null hypothesis and alternative hypotheses are stated as:

$$H_o : \mu = \mu_0$$

$$H_a : \mu \neq \mu_0$$

The null hypothesis, H_o , states that the mean is equal to the value μ_0 and the alternative hypothesis, H_a , states that the mean is not equal to μ_0 , thus being a double-sided test. Because the standard deviation of the tests is not known, a t-test was used. In Table 6 an h value of zero means that the null hypothesis cannot be rejected. The 95% confidence interval represents the range of values that have a 95% probability of containing the true mean of the sample.

	Sample	h-value	p-value	Lower 95% CI	Upper 95% CI
Infinite Resistance	1	0	0.7704	18.6	27.9
	2	0	0.1943	22.4	28.7
	3	0	0.5307	18.0	27.3
	4	1	0.0194	24.4	28.2
	5	0	0.0536	18.4	23.8
0.5 – 5 ohm resistance	1	1	0.0159	13.6	21.9
	2	1	0.0003	16.5	19.2
	3	0	0.1699	16.3	25.6
	4	1	0.0170	13.9	22.1
	5	1	0.0024	18.3	21.4
10 – 100 ohm resistance	1	1	0.0158	16.3	22.4
	2	0	0.0589	14.6	24.0
	3	1	0.0258	13.1	22.6
	4	1	0.0088	16.0	21.7
	5	1	0.0098	13.1	21.1
	6	0	0.3235	12.0	28.8
	7	0	0.0723	16.2	24.3

Table 6. Hypothesis testing results for laminated samples

Figure 10 shows the confidence intervals of the potential efficiency for all the laminated samples graphically. A closer look at the confidence intervals for the data shows that all of the less-than-infinite samples overlap some of the confidence intervals for the infinite resistance samples. While there may be a difference in potential efficiency for infinite interlaminar resistance and less-than-infinite interlaminar resistance TERFENOL-D, it is not clear from the data shown here.

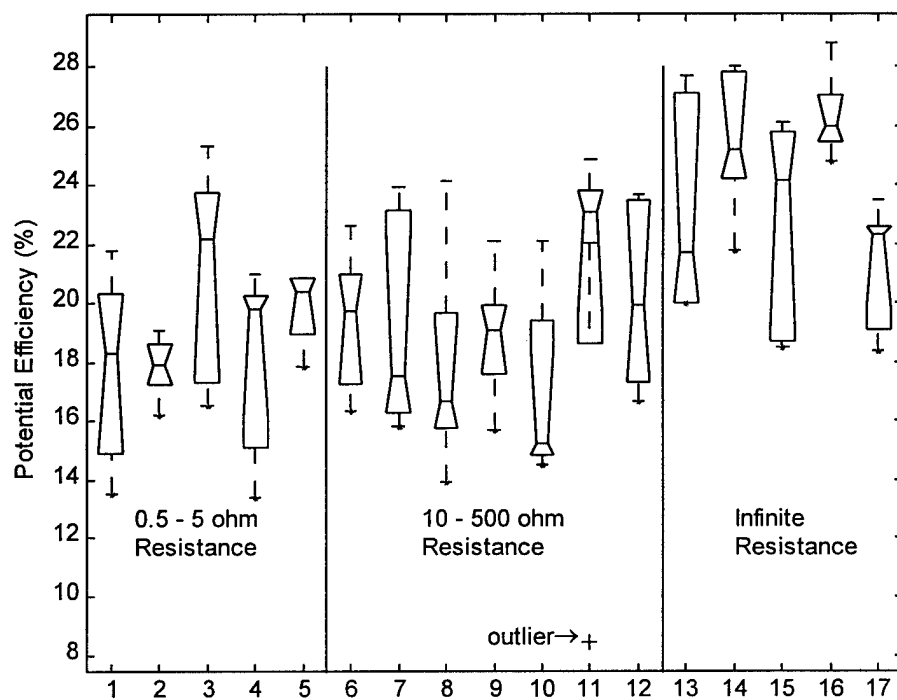


Figure 8. Consolidated potential efficiency data for laminated rods

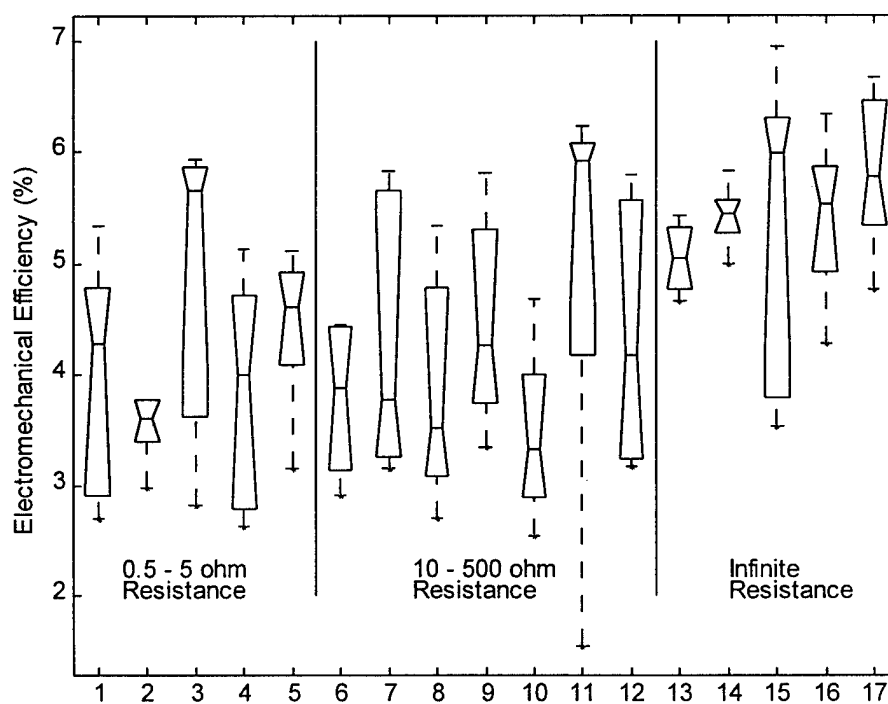


Figure 9. Consolidated electromechanical efficiency data for laminated samples

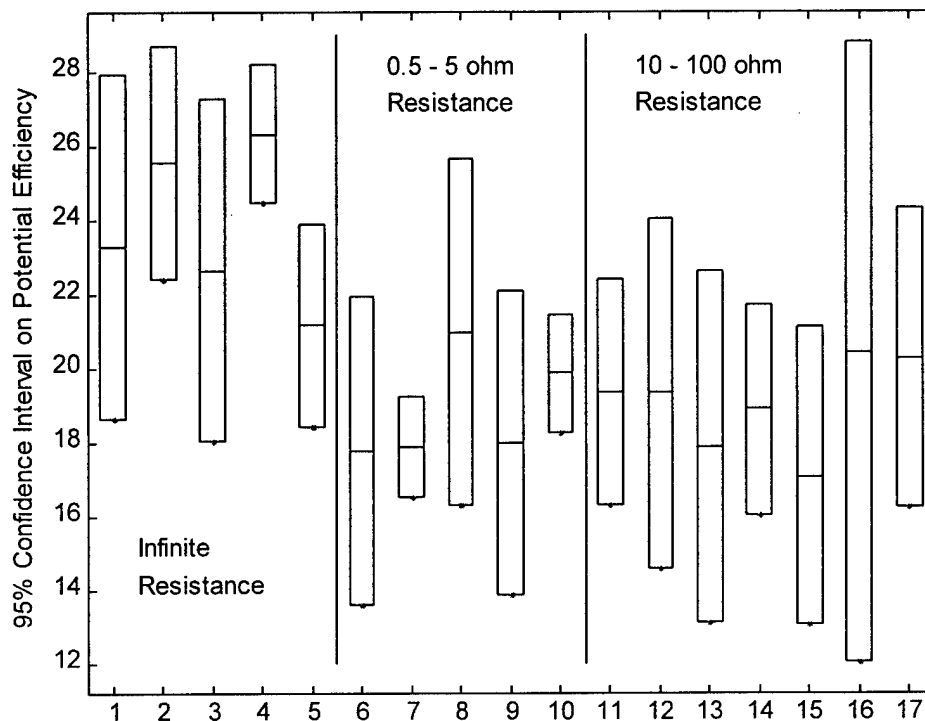


Figure 10. Confidence Intervals for Laminated Samples

V. Conclusions and Recommendations

There is a significant difference between TERFENOL-D rods with no laminations and less-than-infinite interlaminar resistance. Therefore, the benefit of laminating TERFENOL-D is not completely cancelled when a short exists between two lamina.

While there may be a slight difference between infinite resistance and less-than-infinite resistance glue joints, the current test system was not sensitive enough to make a conclusive statement. Either more tests, a more sensitive test system, or an alternative test methodology would be required to draw conclusions about the difference between infinite and less-than-infinite glue joints. However, because of the limited scope of this study, these improved tests were not undertaken.

The Phase I Option will provide more in-depth analysis of the data. Some quantitative analysis regarding eddy current losses in the less-than-infinite samples will be completed. Further investigation into causes of the large variance of the test system will also be completed.

References

1. Lammeraner, J. and Stafl, M., Eddy Currents, CRC Press, Cleveland, OH.
2. Summary Technical Report of Division 6, NDRC, Volume 13, The Design and Construction of Magnetostriction Transducers, Washington, D.C., 1946.
3. Diamond, W.J., Practical Experiment Designs, p. 289, Wadsworth, Inc., 1981.

Appendix A: Operating Procedures

Test Procedure for Lamination SBIR tests

Equipment

HP Spectrum Analyzer (3 data channels)
0.054 ohm sense resistor
Techron 7750 Power Supply Amplifier
DC power supply (BK Precision 1743)
Accelerometer (B&K 2030576 S/N 8309) & Charge Amp (B&K Type 2635)
Temperature Probe
Lamination Test Fixture
Test Samples

Setup

Input current (measured across the sense resistor) -- Channel 1
Input voltage -- Channel 2
Acceleration -- Channel 3
DC bias coil -- Marked lead goes to + terminal of DC power supply
 Unmarked lead goes to - terminal of DC power supply
AC drive coil -- Marked lead attaches to red wire
 Unmarked lead attaches to black wire
Charge Amp -- Sensitivity (399), 0.1-1 range, 10mV/unit out, 1m/s², 2 acc,
upper freq. limit 10 kHz

Operation

1. Leave the accelerometer disconnected from charge amp.
2. Start Analyzer software and recall instrument state "LAMRUN3.STA"
3. Record TERFENOL-D sample ID number, test number
4. Measure the rod temperature using the temperature probe and record the value.
5. Place the sample in the test cell using the magnetic tool provided.
6. Check that the top cap has silicone grease between the output post and the bearing. Add grease if needed.
7. Place the top cap assembly on top of the fixture.
8. Rotate the output rod back and forth on top of the rod.
9. Tighten the top cap until the distance between the accelerometer back and the top cap is 1.041" \pm 0.002"
10. Connect accelerometer to charge amp.
11. Set analyzer power amplifier channel 1 to the 7 mark.
12. Turn on and adjust DC power supply to 2.25 amps.
13. Click Start button on screen.
14. Run one sweep. If an OVERLOAD appears on the screen, abort the run.
15. Do not save the data from the first sweep.
16. Click Start button again.
17. After the run has finished, switch off the DC power supply.

18. Save the data to the file name indicated on the log sheet.
19. Disconnect accelerometer from the charge amp.
20. Remove top cap.
21. Remove sample.
22. Measure and record the sample temperature. If the sample temperature exceeds 40°C, discard the results, wait for the test fixture to cool down, and re-run the test.
23. Repeat with next sample.

Appendix B: Computer Code

All programs are written in Matlab.

```
%Filename: lamm2
%Subroutines: calc
file=input('Enter the File Set designator. ','s');
count=input('First file Number. ');
%count = 1;
number=input('Enter the number of files to be tested. ');
%number = 5;
%file='ec980';number=85;count=332;

%*****
%count=1;
%number=5;
base=count;
for zot=1:number;

    filenamef=['f' file int2str(zot)];
    filenameei=['i' file int2str(zot)];
    filenameeo=['o' file int2str(zot)];

    eval(['load ',filenamef])
    eval(['load ',filenameei])
    eval(['load ',filenameeo])

    clear filenamef filenameeo filenameei c2x c3x c4x c5x o2ilx o3ilx o4ilx
    o5ilx

    calc
    pe(zot,1) = pe2;
    ctrr(zot,1) = a(1);
    ctri(zot,1) = a(2);
    rad(zot,1) = a(3);
    bet(zot,1) = beta2;
    xfer(zot,1) = max(o3il);
    %emff
    % savepe

    clldata

end

% Filename: calc
% Subroutines: divide, cfit, poteff
% This routine calculates the potential efficiency for both real
% data and the fitted circle data. It also calculates the loss
% tangent, beta.
```

```

[x,y]=divide(o2i1);
[a,xt,yt]=cfit(x,y);

pe1=poteff(max(x),min(x));
pe2=poteff(max(xt),min(xt));

% Crossover point

rex=(x(1)+x(length(x)))/2;
imx=(y(1)+y(length(y)))/2;

% beta

beta2=atan((a(2)-imx)./(a(1)-rex));

% Filename: divide

function [x,y]=divide(o2i1)

% This routine separates the impedance data needed to fit a circle
% in order to find potential efficiency.

r=real(o2i1);
i=imag(o2i1);

rmargin=(sum(abs(diff(r)))/length(r))*3;
imargin=(sum(abs(diff(i)))/length(i))*3;

k=0;
for n=1:length(r),
    for m=n+1:length(r),
        if abs(r(n)-r(m)) < rmargin
            if abs(i(n)-i(m)) < imargin
                k=k+1;
                pe(k,1)=n;
                pe(k,2)=m;
            end;
        end;
    end;
end;

rad=0;
for n=1:length(pe),
    vec=r(pe(n,1):pe(n,2));
    if (max(vec)-min(vec)) > rad
        rad=max(vec)-min(vec);
        q=n;
    end;
end;

start=pe(q,1);
stop=pe(q,2);

x=r(start:stop);

```

```
y=i(start:stop);
```

```
% Filename: cfit
```

```
function [a,xt,yt]=cfits(x,y)
```

```
% This routine fits a circle to experimental data by  
% using a weighted least squares method. The weighting  
% is done because the data points are not evenly distributed  
% around the circle.
```

```
d=sqrt(diff(x).^2+diff(y).^2); %distance between points  
theta=d./max(d); %weighting factor  
n=length(x);  
theta(n)=sqrt((x(1)-x(n)).^2+(y(1)-y(n)).^2)./max(d); %between 1st&last  
points  
options(1)=0;
```

```
a0=[sum(x)/length(x) sum(y)/length(y) max(x)-sum(x)/length(x)]; %1st  
guess  
%[a,options]=leastsq('circle2',a0,options,[],x,y,theta);  
a =fmins('circle1',a0,options,[],x,y,theta); %minimizing routine  
%a = [x-center y-center radius]
```

```
c=a(1)+a(3);  
e=a(1)-a(3);  
x1=rot90([e:(c-e)/100:c]);  
x2=rot90([c:(e-c)/100:e]);
```

```
y1=sqrt((a(3).^2-(x1-a(1)).^2))+ a(2);  
y2=-sqrt((a(3).^2-(x2-a(1)).^2))+ a(2);
```

```
xt=[x1;x2];  
yt=[y1;y2];
```

```
% Filename: poteff
```

```
function f=poteff(rmax,rmin)
```

```
% This function calculates the potential efficiency given the maximum  
% and minimum real impedances of a transducer.
```

```
f=(sqrt(rmax)-sqrt(rmin))/(sqrt(rmax)+sqrt(rmin));
```

Appendix C: Laboratory Test Results

STATE OF NEW YORK

Dekko Technical Center

The Right Equation for Testing Your R & D and Manufacturing Solutions

Date: 10/5/98

Requester: Julie Slaughter - ETREMA Products, Inc.

Purpose: Volume Resistivity of Epoxy Plaques
ETREMA project number E184-011

Samples: Material A: Samples 1A, 2A, 3A
Material B: Samples 1B, 2B, 3B
Material C: Sample 1C

Test Date(s): 10/1/98, 10/2/98

Laboratory Conditions: 22.5°C_24%, 22.2°C_49%

Equipment: Micro-ohmmeter - (Keithley 580)
Electrometer / High Resistance Meter (Keithley 6517A)
Resistivity Fixture (Keithley 8009A)
10 lb. Weight
Copper Electrodes - (16 cm² square)
Environmental Chamber - (Blue-M, model FRS-361F)
Super Micrometer (Starrett No. 673 with Analog Output)

Procedure: Measurements were performed using ASTM D-4496 as a reference. All samples were conditioned at 22°C, 50% relative humidity for at least 40 hours prior to measurements.

Resistance measurements were made on sample plaques of materials A and B using copper electrodes and a micro-ohmmeter. The total upper electrode weight was 12 lbs.

Volume resistivity for the sample from material C was determined using an electrometer / high resistance meter with a resistivity fixture.

Results: Table1: Volume resistivity of epoxy samples

	Sample #	Resistance (Ohms)	Thickness (cm)	Volume Resistivity (Ohm - cm)
Material A	1A	0.05	0.196	4.1
	2A	0.065	0.175	5.9
	3A	0.016	0.198	1.3
Material B	1B	0.3	0.155	30
	2B	200	0.167	19,000
	3B	3.5	0.165	340
Material C	1C		0.381	4.14x10 ¹⁵

Some, though not all, of the variability found in material A and material B samples may be due to thickness irregularities

PREPARED BY:

Gavin Replogle

DATE:

10/5/98

REVIEWED BY:

Robert Einhaus

DATE:

10/5/98

All primary data is on file at the Dekko Technical Center and is available upon request.

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